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WEAPON ENGAGEMENT MANAGEMENT FOR SHIP DEFENCE

by

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ABSTRACT

DREV, in collaboration with Lockheed Martin Canada, is investigating the development of a computer-based, real-time decision support system that can provide advanced support capabilities for combat system operators in countering the current and anticipated threat to the Canadian Patrol Frigate. Among its principal roles, this system will: continuously take in data from the ship's sensors and other information sources; support the formulation, maintenance and display of an accurate tactical picture derived by fusing all available data, thus leading to enhanced situation awareness; and assist with the determination and selection of a response to anticipated or actual threats. This document is concerned with the development of a weapon engagement manager for Above Water Warfare that forms part of the system. The manager adaptively plans and directs in real time actions to counter air and surface threats. A generic agent architecture is introduced and current work toward its implementation and performance evaluation in a closed-loop simulation environment incorporating a custom-designed knowledge-based shell is described.

RÉSUMÉ

Le CRDV, en collaboration avec Lockheed Martin Canada, a mis en place un projet de recherche dans le but d'étudier le développement d'un système informatisé d'aide à la décision fonctionnant en temps réel et qui permettra d'améliorer la capacité des opérateurs du système de combat de la Frégate de patrouille canadienne à contrer les menaces actuelles et futures. Un tel système aura comme fonctions principales: de saisir continuellement les données et les informations provenant des capteurs du navire et de sources externes; de fusionner toute l'information disponible dans le but de construire, maintenir et afficher une image tactique précise; d'assister l'usager dans l'interprétation de cette image; et de formuler et fournir l'aide appropriée pour contrer les menaces anticipées ou actuelles du navire. Ce document traite du développement d'un contrôleur de système d'armes pour la guerre en surface faisant partie de ce système. Le contrôleur planifie adaptivement et dirige les actions en temps réel pour contrer les menaces aériennes et de surface. On présente un agent générique d'architecture ainsi que les travaux présentement en cours qui permettront son implantation et son évaluation dans un environnement de simulation à boucle fermée qui incorpore une coquille de système à base de connaissances faite sur mesure.

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EXECUTIVE SUMMARY

Technological advances in threat technology, the increasing tempo and diversity of open-ocean and littoral scenarios, and the volume and imperfect nature of the data to be processed under time-critical conditions will pose significant challenges to shipboard Command and Control Systems and on the operators who must use these systems to defend their ship and fulfil their mission. To address these challenges, DREV is investigating concepts for the design of a real-time decision support system that continuously fuses data from the ship's sensors and other sources, helps operators maintain situation awareness, and supports their response to actual or anticipated threats.

This document is concerned principally with support for weapon engagement management in Above Water Warfare that forms part of the system. The manager plans and directs in real time actions involving use of hardkill and softkill weapons to counter air and surface threats. We propose an agent architecture that dynamically interleaves planning and execution as it adapts to unanticipated changes in the tactical situation. The architecture integrates both reactive and deliberative planning. Deliberation is based on projecting the currently perceived situation and may incorporate plan contingencies to handle action outcome and situation uncertainty. Reactive planning is driven by precompiled stimulus-response knowledge (e.g., tactical doctrine). Local control of architectural components to allow for varying computational resources and time criticality for producing deliberative plans is also briefly examined.

This document also describes ongoing work toward the implementation and performance evaluation of the weapon engagement manager in a closed-loop simulation environment incorporating a custom-designed knowledge-based system shell.

The results of this research are expected to contribute to DREV's ongoing investigation of enhancements to the HALIFAX Class Command and Control System as part of its mid-life upgrade thus ensuring that the ship can counter new challenges well into the next century.

LIST OF ACRONYMS

AAW	:	Anti-Air Warfare
AI	:	Artificial Intelligence
ASM	:	Anti-Ship Missile
AWW	:	Above Water Warfare
C2	:	Command and Control
CCS	:	C2 System
CE	:	Co-operative Engagement
CEC	:	Co-operative Engagement Capability
CIWS	:	Close-In Weapon System
CO	:	Commanding Officer
CPF	:	Canadian Patrol Frigate
CPU	:	Central Processing Unit
CRAD	:	Chief Research and Development
CRDV	:	Centre de recherches pour la défense Valcartier
DF	:	Data Fusion
DFRM	:	Data Fusion and Resource Management
DMSS	:	Directorate Maritime Ship Support
DND	:	Department of National Defence
DNR	:	Directorate Naval Requirements
DRDB	:	Defence Research and Development Branch
DRE	:	Defence Research Establishment

DREO	:	Defence Research Establishment Ottawa
DREV	:	Defence Research Establishment Valcartier
DSAM	:	Deputy Scientific Advisor Maritime
DSS	:	Decision Support System
ECM	:	Electronic Countermeasures
ESM	:	Electronic Support Measures
EWS	:	Electronic Warfare Supervisor
HCI	:	Human-Computer Interface
IEEE	:	Institute of Electrical and Electronic Engineers
IFF	:	Identification Friend or Foe
IR	:	Infrared
IRST	:	Infrared Search and Track
JDL	:	Joint Directors of Laboratories
KBS	:	Knowledge-Based System
MSDF	:	Multi-Sensor Data Fusion
MTP	:	Maritime Tactical Picture
NETE	:	Naval Engineering Test Establishment
OODA	:	Observe-Orient-Decide-Act
R&D	:	Research and Development
RM	:	Resource Management
SAM	:	Surface-to-Air Missile
SA	:	Situation Awareness
SRTE	:	Simulated Real-Time Environment

STA	:	Situation and Threat Assessment
STIR	:	Separate Track and Illumination Radar
TA	:	Threat Assessment
TEWA	:	Threat Evaluation and Weapon Assignment
TRUMP	:	Tribal class Update and Modernization Project
WEM	:	Weapon Engagement Management

1.0 INTRODUCTION

Technological advances in threat technology, the increasing tempo and diversity of open-ocean and littoral scenarios, and the volume and imperfect nature of the data to be processed under time-critical conditions will pose significant challenges to shipboard Command and Control Systems (CCSs) and on the operators who must use these systems to defend their ship and fulfil their mission. The Data Fusion and Resource Management Group at Defence Research Establishment Valcartier (DREV) and the R&D department at Lockheed Martin Canada (LMC) have for several years now been investigating concepts to continuously integrate data from a ship's sensors and other sources, dynamically maintain a tactical situation picture, and support response to actual or anticipated threats. The two organisations are now jointly involved in a project to design, develop and implement a real-time decision support system (DSS) that can be integrated into the ship's CCS to support operators in their tactical decision making and action execution activities, with particular focus on application to the mid-life upgrade of the HALIFAX Class Command and Control System expected early in the next century.

This document is concerned with weapon engagement management (WEM) in Above Water Warfare (AWW), which forms an important part of the resource management support capability of the DSS. The aim of the document is to review background information and define the concept of WEM, and to propose a generic model and software architecture for WEM. Finally, ongoing work in a collaborative DREV/LMC project which is implementing WEM based on this model is discussed.

This document is organised as follows. Chapter 0 provides background information on the tactical Command and Control (C2) process and a discussion of the high-level framework of the DSS. Chapter 0 exposes the context of weapon engagement management with respect to general concepts of data fusion and resource management. Chapter 0 examines general requirements of resource management. Chapter 0 outlines a high-level model of generic weapon engagement management, discussing both the software architecture and the problem of handling real-time constraints. Chapter 0 describes the DREV/LMC project which is currently implementing WEM based on the generic model discussed here. Chapter 0 provides conclusions.

This work was carried out at DREV between January and April 1997, under Work Unit 1ba12: "Investigations of MSDF/STA/RM Concepts".

2.0 SHIPBOARD COMMAND AND CONTROL AND TACTICAL DECISION MAKING

2.1 Tactical Command and Control Process

In a modern frigate like the HALIFAX Class ship, also known as the Canadian Patrol Frigate (CPF), most tactical decision making is performed within the ship's Operations Room. There, a team of combat system operators interact with a CCS through consoles, aided by a number of other systems. They perceive and interpret information available from ownship sensors or data-linked from other co-operating platforms, and plan and conduct mission operations.

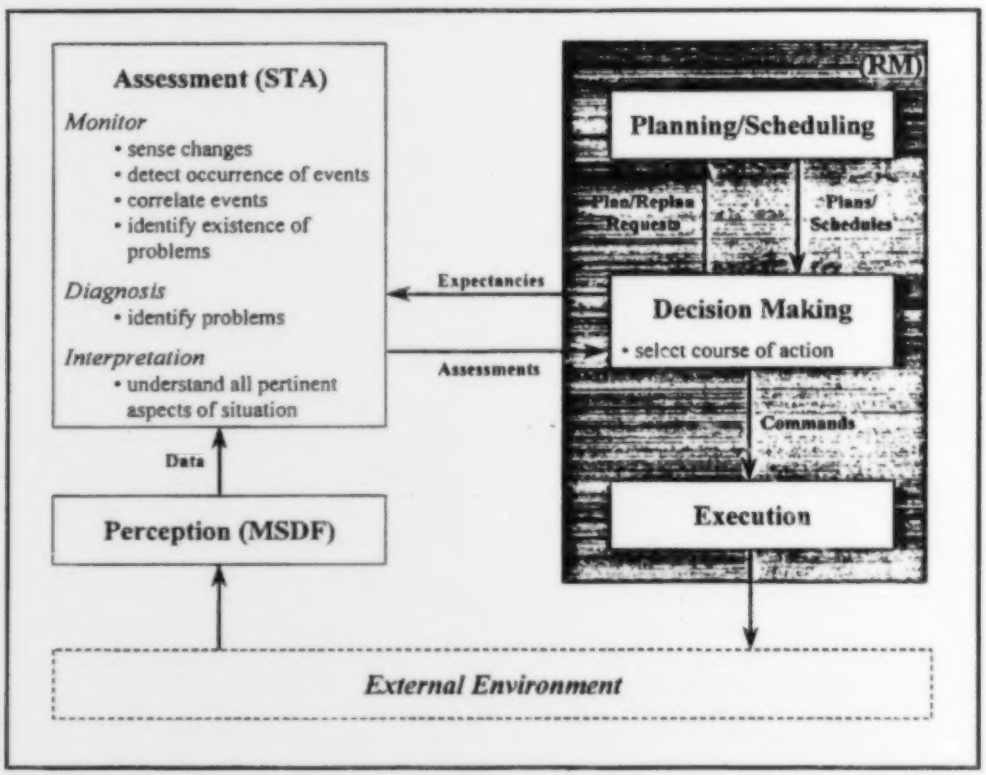

FIGURE 1 - Operator activities in the C2 process

Major C2 tasks include: weapon and sensor systems control, tactical picture compilation, situation interpretation and threat evaluation, weapon selection and

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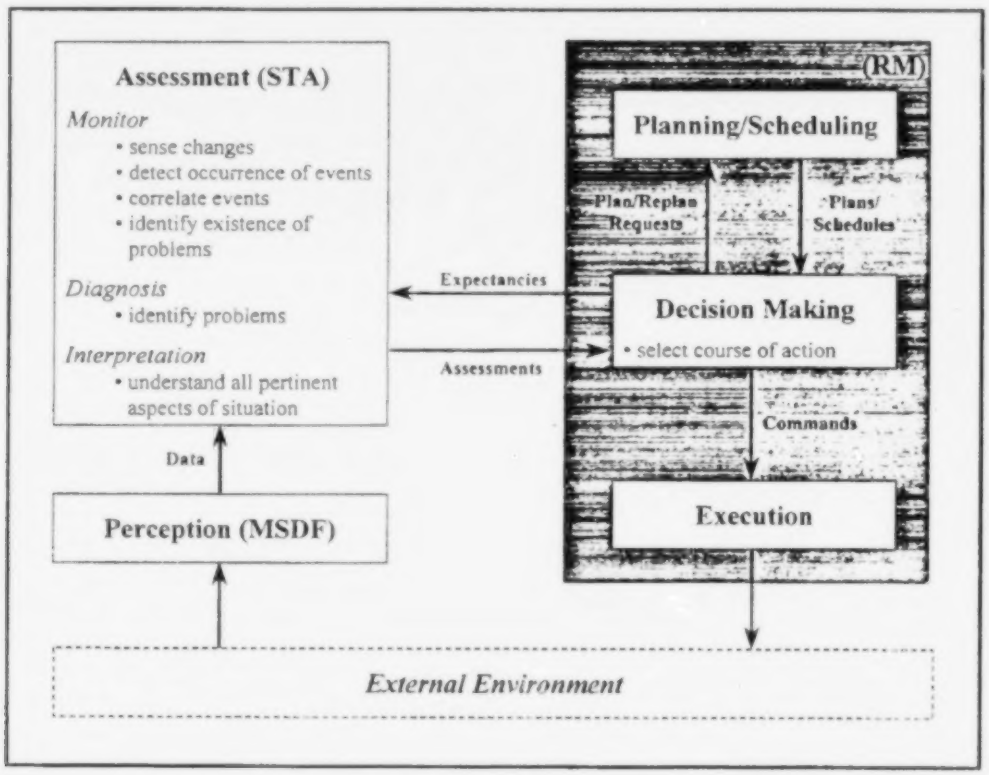

FIGURE 1 - Operator activities in the C2 process

Major C2 tasks include: weapon and sensor systems control, tactical picture compilation, situation interpretation and threat evaluation, weapon selection and

engagement monitoring, navigation and ship manoeuvres, and mission planning and evaluation. The C2 process necessitates a highly dynamic flow of information and decision making involving a number of operators, with a concomitant requirement for developing a common, shared representation of the situation. We now describe this process in more detail.

The ship's command structure is organised hierarchically. Although the Commanding Officer (CO) is responsible in all respects, he normally delegates control and charge of the ship to personnel of his choice to allow the most efficient deployment of the ship. Effective tactical C2 is the result of a co-ordinated team effort and communication among its members is critical in sharing information relevant to the mission and the decision-making tasks involved. Various means of communication are provided to enable this. For example, team members monitor information disseminated to and from other units at sea and ashore, communicate with each other and provide feedback, when required, by means of headphones. In addition, stateboards promulgate current information on perceived threats and assist in activating pre-planned responses to highly time-stressed events such as the sudden detection of an anti-ship missile (ASM) flying toward the ship.

Collectively, the various tactical C2 tasks involve operators in a number of perceptual and cognitive processing activities. For example, with respect to the event sequence from "birth" to "death" of a single air or surface contact, they span the moments from first contact detection (perception), its investigation, assessment and evaluation in the context of the current mission (situation and threat assessment), development of one or more courses of action (planning/scheduling), to an engagement or course of action decision (decision making) and monitoring of the potential ensuing engagement (execution). A high-level representation of these various operator activities, including some key sub-processes of assessment, are shown in Fig. 1.

The principal activity loop in Fig. 1 involving perception, assessment, decision making and execution is characteristic of the well-known Boyd cycle or Observation-Orientation-Decision-Action (OODA) loop (Ref. 1). Boyd theorised that each party in a conflict engages in a cyclical process. In a single cycle, the situation is first observed. On this basis, an orientation toward the situation is developed in the form of a mental

model, accounting for situation opportunities and vulnerabilities. Finally, a course of action decision is made and implemented.

The AWW work environment is even more demanding than the above snapshot of activities related to just a single contact suggests. At any moment, numerous contacts may have been detected, with each contact at its own point of processing. In addition to being monitored within individual activity cycles, contact relationships (functional groups, spatial groups, etc.) need to be monitored for additional clues to their identity, intentions and tactical significance to the mission.

Perceptual and cognitive processing is further complicated by the fact that the underlying information is derived by continuously integrating or fusing data from a variety of organic sources (under ownship control) and non-organic sources (not under ownship control), including radar, electronic support measures, infrared search and track, identification friend or foe transponder responses, as well as intelligence information from shore and various deployed units, to build a coherent Maritime Tactical Picture (MTP) of the ship's area of interest. Particular processing problems include: non-organic information is generally less timely than organic information which makes it difficult to correlate the two types of information; the data to be integrated is generally imperfect – it can be uncertain, incomplete, imprecise, inconsistent, and ambiguous, or some combination of these, due to limited sensor coverage, report ambiguities, report conflicts, or inaccuracies in measured data (Ref. 2). It follows that operators may have to handle potentially large situation uncertainties and at any given moment there may be several likely interpretations of the tactical situation. This leads to processing large volumes of data under stringent time constraints. At present, in the CPF for example, these various fusion tasks are performed manually by operators.

All of this calls for operators to work effectively in a highly co-ordinated manner toward common objectives. They must: (i) continuously scan consoles and monitor communication nets for significant events and alerts; (ii) exchange information among themselves or pass information up the chain of command; (iii) issue or respond to orders depending on an operator's position and role in the chain of command; and (iv) focus attention at any given moment among several competing stimuli and divide attention between several competing or complementary multiple tasks in response to operator-specific goals.

In fact, so much needs to be done at any given time that careful attention and time management at both the individual operator and team levels are important for effective performance. Critical incidents happen at indeterminate times, resulting in dynamically shifting, multiple goals and numerous perceptual and cognitive tasks to be performed by various operators toward co-operatively accomplishing these goals. The result is a complex, dynamic, real-time, data- and goal-driven multi-tasking environment in which goals are continuously created, prioritised and steps taken toward their achievement with continuous attentional shifts between goals dictated by their time-dependent relative priorities. It is therefore vital that both human and machine resources, including weapons, sensors, computers and communications, are effectively managed. Such problems are particularly difficult when careful scheduling of shared resources is required to achieve time-constrained goals.

We have described the complexity of the AWW environment in terms of the cognitive demands imposed on operators. Woods (Ref. 3) states that there are four dimensions that define the cognitive demands of a work domain: dynamism, the number of its parts and the extensiveness of interconnections between those parts, uncertainty, and risk. It is evident that AWW rates as a highly cognitively demanding work domain in all these dimensions. In practice, complexity can vary, depending on the nature of the conflict. Future combat scenarios are expected to span low to high intensity levels of conflict in open ocean and littoral (i.e., near land) areas. In high clutter, terrain-masked littoral environments, there may be many kinds of platforms of many nationalities with potential for interactions with neutrals becoming embedded within engagements. Thus, establishing, identifying the numerous contacts, determining their intentions, interpreting dynamic, complex rules of engagement and taking appropriate action will be very challenging operator tasks. Complexity also increases with advances in missile technology (e.g., higher speeds, sea skimming attack profiles, smaller signatures) that lead to reduced detection ranges and reaction times against such threats.

2.2 High-Level Framework of a Real-Time Decision Support System

Section 2.1 highlighted the cognitive demands of shipboard AWW. In highly dynamic scenarios with a large number of contacts, handling the large amounts of data could quickly overwhelm human capabilities. Moreover, human information processing is subject to a number of limitations and deficiencies, such as finite cycle time, limited

working memory, limited ability to perceive and process information and cognitive biases. It is also negatively impacted by environmental factors or stressors and almost random errors or slips. This suggests a need for tools to support the strengths and complement the weaknesses of operators by matching their perceptual and cognitive resources to the demands of the AWW environment and by supporting, when necessary, their mental strategies used to deal with complexity and perform decision making activities. In particular, such tools should support at least the following two complementary areas: (i) the fundamental competence of combat system operators; and (ii) their information processing limitations and deficiencies. The first type of support is aimed at bridging the gap between the novice and the expert operator, as well as enhancing the competence of both the individual and the team, be they novice or expert in their tasks. The second type aims to compensate for degraded or limited human performance at both the individual and team levels, particularly in highly stressing and dynamic situations.

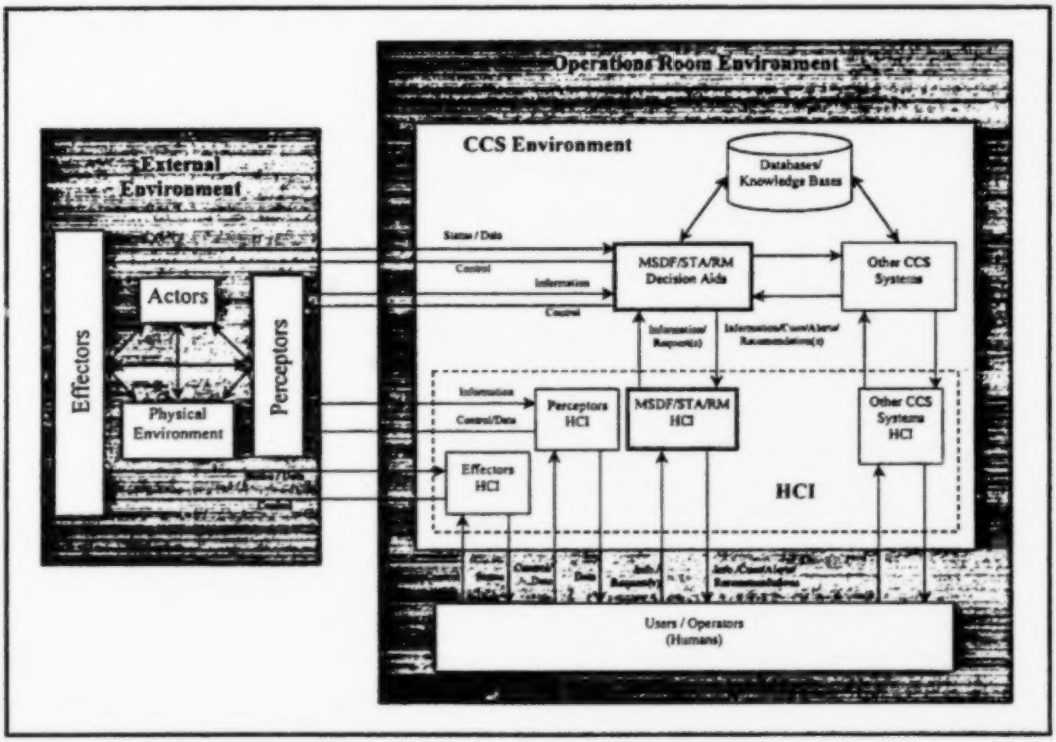

FIGURE 2 - Operations room environment with an MSDF/STA/RM DSS

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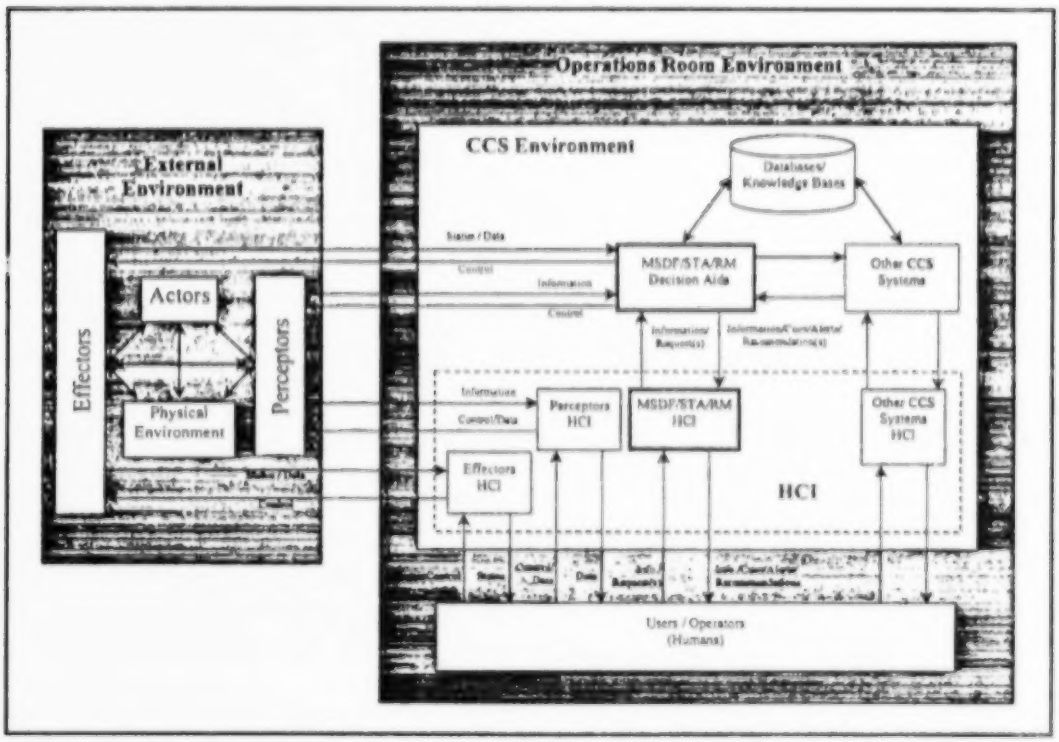


FIGURE 2 - Operations room environment with an MSDF/STA/RM DSS

This work is part of a continuing investigation aimed at designing a real-time decision support system (DSS) that can provide the required support. Specifically, this DSS is expected to support operators in: (i) the fusion of data from the ship's sensors and other sources; (ii) the formulation, maintenance and display of an accurate dynamic situation picture, leading to enhanced situation awareness; (iii) the identification and selection of courses of action in response to anticipated or actual threats to the mission; and (iv) action implementation once a decision to act has been made and is being carried out. With respect to particular DSS capabilities, item (i) relates to its Multi-Source Data Fusion (MSDF) capability. It supports perception activities in Fig. 1. Item (ii) relates to its Situation and Threat Assessment (STA) capability. It supports assessment activities in Fig. 2. Finally, items (iii) and (iv) relate to its Resource Management (RM) capability. It supports planning/scheduling, decision making and execution activities in Fig. 1.

It is envisaged that this DSS, which we refer to as an MSDF/STA/RM system, will become an embedded component of the ship's combat system, integrated within the CCS. A high-level perspective of this integration is shown in Fig. 2. The environment in Fig. 2 is decomposed into the portion within the ship's Operations Room and the portion outside, including the perceptors (organic and non-organic information sources), effectors (active and passive weapon systems), the actors (threats, friends, neutrals) and the physical environment external to the ship. The CCS environment is everything in the CCS of a hardware or software nature, including the various human-computer interfaces (HCIs), databases/knowledge bases and other CCS systems. These databases/knowledge bases contain a variety of a priori knowledge, including standard operating procedures, and strategic, Electronic Warfare (EW) and intelligence information.

3.0 CONTEXT OF WEAPON ENGAGEMENT MANAGEMENT

3.1 Data Fusion

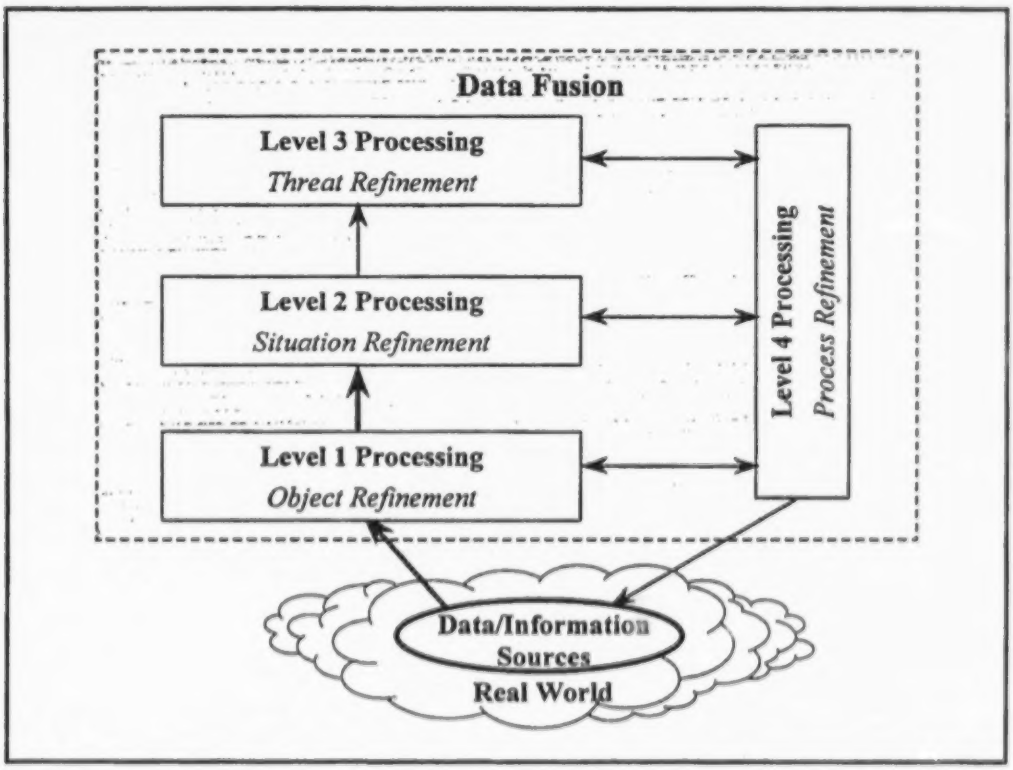


FIGURE 3 - The JDL data fusion model

Advances in technology leading to a rapid increase in the volume of sensor data and the deployment of more sophisticated weapons have fundamentally altered the information processing problem in C2. One of the most important emerging concepts is data fusion. Based on the work of the Joint Directors of Laboratories (JDL) Data Fusion Subpanel, Waltz and Llinas have defined data fusion as "a multilevel, multifaceted process dealing with the detection, association, correlation, estimation and combination of data and information from multiple sources to achieve refined state and identity estimation, and complete and timely assessments of situation and threat" (Ref. 4). The process is also characterised by continuous refinements of its estimates and assessments,

and by evaluation of the need for additional data and information sources, or modification of the process itself, to achieve improved results. Data fusion is therefore a many layered processing strategy.

Figure 3 shows the four processing levels defined in the JDL data fusion model. In this representation, only multi-source data samples of the real world are available. An improved interpretation of the real world will be facilitated by data fusion processing. The arrow widths in the figure represent the relative data bandwidths between the processing levels. Each successive level represents a higher level of abstraction and refinement. Level 1 processing corresponds to Multi-Source Data Fusion (MSDF) described in Section 2.2, while Level 2 and Level 3 processing form the basis for Situation and Threat Assessment (STA), also described there. In Level 4 processing, inferences drawn from the data fusion system may be used to select and/or control the input sources, or alter the fusion techniques themselves. The connection to general resource management issues is described in the following subsection.

3.2 Resource Management

The broadest concept of resource management for AWW on a naval platform like the CPF entails dealing with both system resources, which are used to provide input or support for processing functionality, and tactical resources, which are used to affect the environment to achieve some tactical or operational goal. System resources include "base systems" (e.g., CPU, memory, bandwidth) and software processes (e.g., algorithm choices). Tactical resources include weapons (e.g., missiles, guns, tracking and illuminating radars) and navigational mechanisms (e.g., control of vessel speed and direction). Some resources may be considered either system or tactical depending upon the context in which they are used. For example, sensors and communications equipment are primarily used as system resources to provide information to the data fusion process, but in general they could also be used actively to convey or confirm presence for tactical reasons, or to supply disinformation (deceptive countermeasures). Similarly, human resources may be system resources in the context of supplying information or process control, or they may be part of the tactical response to a given situation.

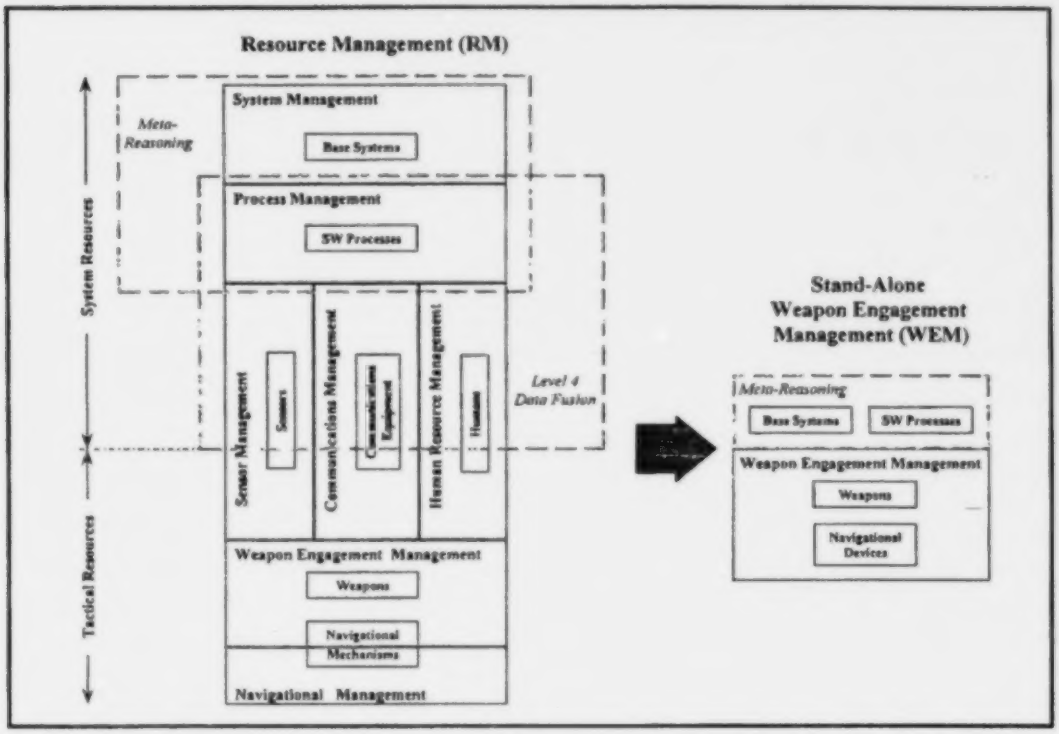


FIGURE 4 - The general concept of RM and WEM for a naval platform

Figure 4 illustrates the general concept of RM for a naval platform. The aforementioned system and tactical resources are indicated, along with the relevant RM processes that utilise these resources. The figure shows the RM processes that correspond to Level 4 Processing in the data fusion model presented in Fig. 3. Also shown are the primary RM processes that constitute meta-reasoning (i.e., reasoning about system reasoning processes, or making plans for system resources which require those same system resources in the planning process), although the case could be made that in certain circumstances Communications Management and Human Resource Management could be regarded as part of Meta-Reasoning (e.g., for the co-ordination of Operations Room team members and some of their activities).

Figure 4 can also be seen in the context of the OODA loop described in Section 2.1. The management processes that are associated with tactical resources affect the Decision and Action portions of the loop. The Level 4 Data Fusion processes affect

primarily the Observation and Orientation portions of the loop (through sensor control or by altering fusion techniques). The meta-reasoning process can impact all portions of the OODA loop.

The WEM subsystem, which is the focus of this document, is the specific component of the RM system responsible for supporting the command team in managing all actions associated with the use of hardkill and softkill weapon systems. Hardkill is aimed at physically destroying a threat by collision or explosion. Softkill is directed at the control and guidance subsystems of an ASM in an attempt to divert it away from its target; it is effected by EW systems using various electronic countermeasures, including confusion, distraction, deception, and seduction (Ref. 5). WEM also entails providing recommendations of ship manoeuvres for supporting weapon deployment and improving weapon effectiveness. In this model, navigational manoeuvres are scheduled and controlled by a separate Navigational Management process that is not part of WEM. The WEM subsystem plans, co-ordinates and directs in real time defence actions at the single ship (self or area defence) or force command (co-operative engagement) levels. Co-operative engagement (CE) involves integrating multiship weapon systems.

In general then, WEM is a single process within RM. However, it is often useful to consider stand-alone WEM, particularly in the initial phase of development of an RM system, or for studying and developing enhancements to a WEM system. Figure 4 shows the components of a stand-alone system in the context of the fundamental RM processes. Note that the meta-reasoning capability for system resources, likely a scaled down version of the System and Process Management processes from the general RM system, has been accommodated. The general requirements of RM examined in Chapter 0 apply equally to WEM. A high-level model of a generic WEM system is outlined in Chapter 0, and a description of an implementation of a stand-alone WEM system is given in Chapter 0.

4.0 GENERAL RESOURCE MANAGEMENT REQUIREMENTS

The RM component of the MSDF/STA/RM decision support system is required to continually interact with operators and a dynamic external environment, synchronising its actions with significant occurrences in this evolving world while respecting critical timing constraints on its behaviour.

Assessments of the situation, together with operator interaction via an HCI, drive RM planning for allocating and scheduling the use of critical resources. Operator interaction can take the form of commands and/or requests for support. This may entail informing or advising operators by providing warnings, recommendations, suggestions, resource allocation plans/schedules, etc., depending on support requirements and on the division of authority to act between the DSS and the operator. Planning a course of action involves reasoning in time and about time. Planning may be triggered periodically (e.g., as a result of sensor input) or aperiodically (e.g., due to sporadic interactions with the operator).

There are various approaches to supporting decision making. For example, under specific conditions in contexts approved in advance by an operator, the system could make decisions and act on his behalf. Another possibility is to provide fixed levels of operator-system control varying in the amount of authority to act that is assigned to the system.

RM must also provide control support once a decision to act has been made and the action is being carried out. This can involve, for example, expanding high-level plans to issue specific commands to individual resource systems (e.g., sensors, weapons). In addition, the inherent dynamism of the environment and the imperfect knowledge of this environment at any given moment requires continuously monitoring its state and the effects of executed actions to recognise significant occurrences that necessitate reactively adapting or repairing previous plans or formulating entirely new responses.

The rate of significant occurrences in the world may be time-dependent. The time to formulate and execute a response may therefore vary from one planning episode to the next, as a function of hard and soft real-time constraints depending on situation context. In the area of weapon management for AWW, this time is extremely limited; it

generally ranges from a few minutes to a few seconds. Conceptually, resource management should strive to optimise the expected "eventual degree of mission accomplishment", from the perspective of the military personnel involved. Internal planning models must therefore be consistent with their beliefs and goals to ensure that what the RM system is trying to achieve is indeed what is desirable to achieve and that the overall effect is to improve the operational effectiveness of the joint operator-machine system.

5.0 A HIGH-LEVEL MODEL OF GENERIC WEAPON ENGAGEMENT MANAGEMENT

5.1 Software Architecture for a Weapon Engagement Manager

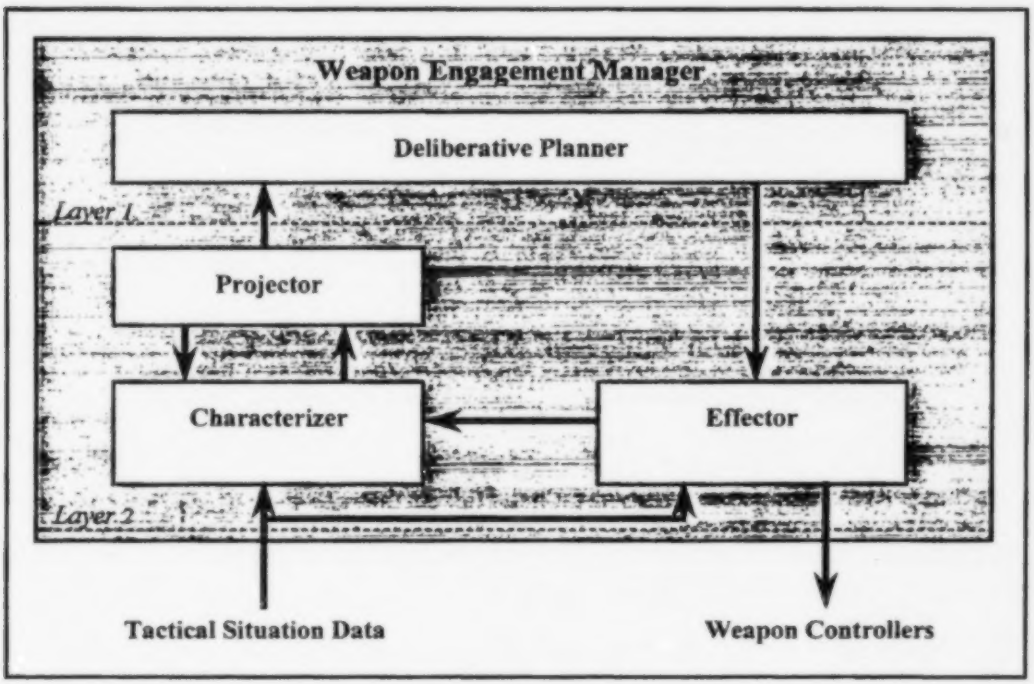
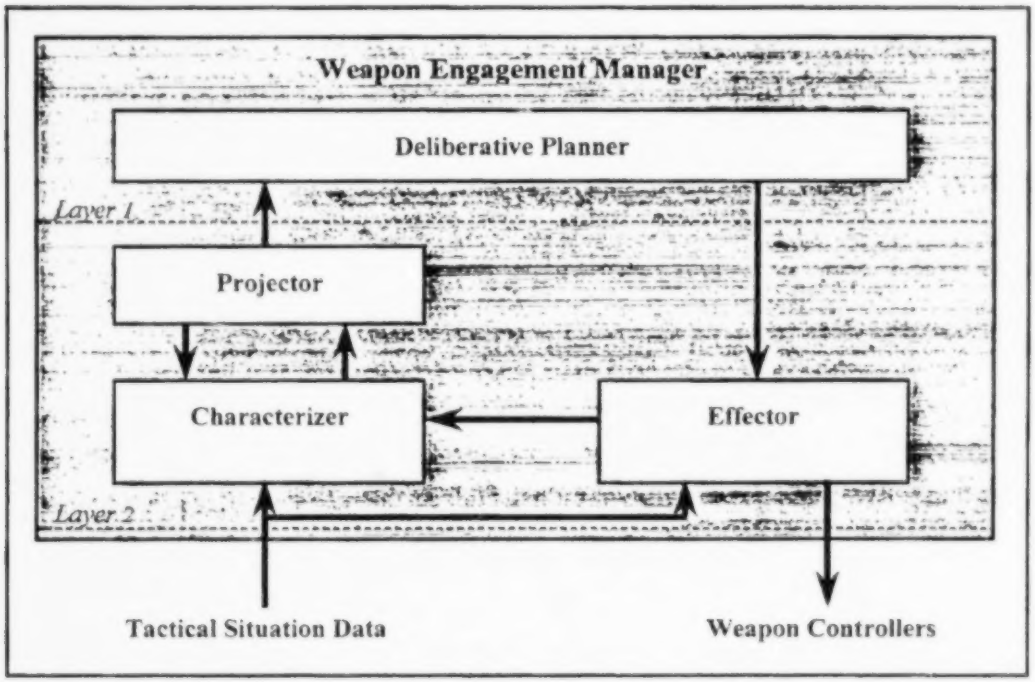


FIGURE 5 - Layered architecture

Both autonomous and supportive behaviours are required in a weapon engagement manager. The manager continually senses and reacts to occurrences, including events that take place in the combat environment and actions or activities involving WEM intervention. It responds to requests for support or commands from an operator. The design couples both feedback and feedforward control to permit dynamic interleaving, and even overlapping, of incremental planning and execution of plans. Feedback control relates to reactive response to immediate change. Reactive planning has a very short term horizon. It is driven by precompiled stimulus-response knowledge (rules, tactical procedures, etc.) that provides almost immediate response depending on the current state of the world. However, it is also guided by deliberative input.

5.0 A HIGH-LEVEL MODEL OF GENERIC WEAPON ENGAGEMENT MANAGEMENT

5.1 Software Architecture for a Weapon Engagement Manager



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Feedforward control involves high-level deliberation based on projecting the perceived history of past and ongoing occurrences over some forecast horizon. Deliberation can be viewed as deep planning over a dynamic look-ahead horizon. It is generally accepted within the artificial intelligence (AI) community that "some balance between quick responses to environmental change and time for deliberation to allow reasoning about what actions to perform seems to offer the best hope for truly adaptive, intelligent agents" (Ref. 6).

WEM uses a variety of knowledge, including knowledge about the behaviour of entities in its combat environment, of engagement doctrine and tactics, and of conditions for the feasibility of specific actions as well as their (stochastic) effects. The manager continually adapts its reasoning to take account of an evolving picture of the tactical situation, computational resources available for reasoning, response time, and the interdependence between reasoning (planning) and the quality of the information on which it is based (sensing). Resource-bounded reasoning to permit dynamically trading off plan quality against computational cost and response time is therefore required. In addition, imperfect information and incomplete knowledge about enemy intentions and behaviour imply that deliberative plans must guide action, not control it.

We now review our software architecture for WEM. A two-layered architecture for the manager is used to hierarchically decompose the functions of WEM, with various world models distributed among the layers. A fundamental consideration is Saridis' principle (Ref. 7) of combining "increasing intelligence with decreasing precision", whereby reasoning in one layer is used to influence, but not control, actions in a lower layer which interacts more directly with the world. Figure 5 shows the decomposition of the principal functions (represented by blocks) and information flows (represented by arrows). Interactions with the operator are omitted.

The deliberative planner responds to significant changes in the tactical picture that require (re)planning. It computes a plan, subject to engagement doctrine and resource availability, for assigning and scheduling use of hardkill and softkill weapon systems and tracking and guidance systems over a plan horizon within the forecast horizon.

The projector extrapolates the perceived world state over the forecast horizon. This includes: extrapolating potentially hostile tracks and ownship manoeuvres;

predicting occurrences of events arising from ongoing engagements, previously committed actions, etc., including outcomes of defence actions and threat strikes on own ships; predicting when potentially hostile tracks will be engageable, from which ships and by which weapon systems on such ships, as well as measures of effectiveness of such defensive actions; predicting effects or restrictions associated with obstructions (parts of a ship's structure, chaff clouds, offboard decoys, etc.), environmental conditions, and/or operational constraints (electromagnetic emission control, risk of fratricide, etc.) which prevent threat interception, or which may significantly degrade the effectiveness of such actions; and predicting positive and negative interactions (Ref. 5) that result from concurrent use of hardkill and softkill weapon systems.

By communicating with individual weapon controllers, the effector co-ordinates and directs execution of plans and uses tactical situation inputs to determine the effectiveness and outcomes of defensive actions. Its actions are based on reactive planning, and, if time allows, on guidance received from deliberation. Since deliberation is based on projection, the effector also implements reactive plan repair strategies when it detects real-time deviations from projections that are "small". Tracks that fail to be engaged according to plan are fed back via the characterizer for replanning. Replanning is triggered by the characterizer signalling the projector to send its latest projections to the planner. This is driven by a number of asynchronous occurrences, including a requirement to extend the window of the latest plan, an operator's request to reshape the defence response, and updates in the tactical picture such as detections of new tracks whose estimated times of first engagement fall within the window of the plan currently being executed.

A weapon controller is cued by the effector. A cue activates a low-level process for using a specific weapon system. The controller also monitors any servo loops associated with this process. There are two data paths in the architecture leading from the arrival of situation assessment input to the generation of weapon cues. The first is via the effector in layer 2 only. This path effects reactive plan modifications due to changes in the tactical picture. The second path is via both layers 2 and 1 and involves deliberation. While response to change along this path is fast, it is not on the same time scale as that on the other.

5.2 Handling Real-Time Constraints

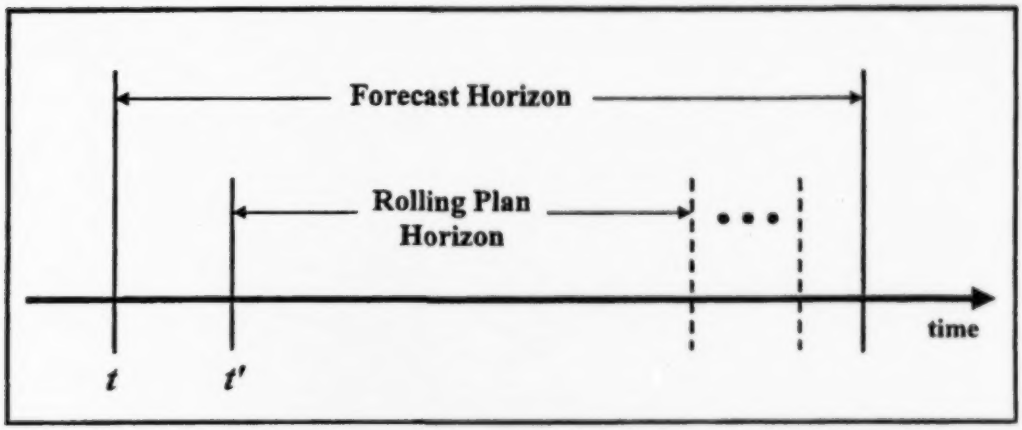


FIGURE 6 - Rolling plan horizon

The requirement that the weapon engagement manager respond within real-time constraints to occurrences in the combat environment and operator commands necessitates explicit modelling of its real-time behaviour if predictable performance is to be achieved (Ref. 8). It is based on the idea of a time-dependent planner (Ref. 9) varying deliberation according to time pressure. It provides service in one of two anytime modes, viz., contract or interruptible. In contract mode, it produces a plan within a specified amount of computing time. In interruptible mode, this time is not specified and it must be capable of returning a plan even if interrupted unexpectedly. One way of achieving the anytime property is to use a rolling plan horizon (Fig. 6) whose size is determined at the time t of a service call. In Fig. 6, for example, the planner must compute a plan within the time interval from t to t'. The plan itself is to be implemented over a time window of the determined size that the situation picture at time t suggests can feasibly be implemented by the effector commencing at time $t' > t$.

6.0 IMPLEMENTATION OF WEAPON ENGAGEMENT MANAGEMENT BASED ON THE GENERIC MODEL

6.1 Project Overview

We are currently implementing an integrated MSDF/STA/RM system for real-time decision support in a naval CCS. The WEM in this system is based on the generic model and architecture described in Chapter 0. The best way to reproduce the features of this model is with an agent-based WEM system. The initial implementation is intended as a simplified system that will serve as a proof-of-concept and the basis for future research and development. Consequently, we have chosen to restrict RM to the stand-alone WEM depicted in Fig. 4, and to limit the scope of WEM to: (i) anti-air warfare (AAW); (ii) CPF-like hardkill weapons only, consisting of surface-to-air missiles (SAMs) and an intermediate range gun (which are supported by two tracking and illuminating radars), and a close-in weapon system (CIWS); and (iii) ownship self defence.

Furthermore, we have adopted an incremental build approach even for this initial implementation. The first phase consists of a prototype that uses only a totally automated mode of operation (i.e., no operator interaction), a simple reactive planner and plan repair mechanism (analogous to CPF CCS functionality in its Automatic Engage mode of operation), and no deliberative planning. This prototype incorporates the core infrastructure functionality described in Section 6.2. This prototype has been successfully completed and tested, and will evolve through several successive builds (e.g., adding deliberative planning, as outlined in Section 6.4) to reflect the capability stated above. Subsequent work is also planned to extend the initial implementation to include both hardkill and softkill weapons, co-operative engagement capability (CEC), and other enhancements to support complete RM and integration into a DSS.

6.2 Description of Knowledge-Based System

A Knowledge-Based System (KBS) architecture provides the infrastructure for the integrated MSDF/STA/RM system described in Section 6.1. The requirements of this KBS that are relevant to WEM include: (i) support for real-time WEM processing; (ii) support for a WEM system comprised of independent processing (intelligent) agents; (iii) support for operation in a multiprocessor environment; (iv) mechanisms to prioritise,

schedule, (re)distribute, and control WEM processing tasks; (v) support for diverse knowledge representations; (vi) mechanisms for forward and backward chaining; (vii) methods for handling information uncertainty; (viii) alertness to new or incoming events; (ix) mechanisms to support failure management (failures due to unforeseen events); and (x) from a development standpoint, support for progressive implementation and scalability.

Because no commercially available KBS shell satisfied the stringent requirements for system capability and performance, a KBS shell was designed, developed, and is being implemented for this project. The essential concern for optimising run-time performance precluded adopting the conventional approach of coding the KBS with interpreted languages (e.g., Lisp or Smalltalk) because they inherently introduce lower efficiency for the benefit of simplicity and ease of implementation. Consequently, a compiled object-oriented language was used.

The KBS has been implemented as a "blackboard" system. The blackboard architecture is preferred and is known to be well suited to deal with the above requirements (Ref. 10), and has been used to develop applications for data fusion (Ref. 11) and planning and scheduling (Refs. 12-14). The blackboard architecture is modelled on the analogy of human experts working together by exchanging and interpreting each other's beliefs and questions by interacting on a shared blackboard (Refs. 15-16). The blackboard system is comprised of three main components: knowledge sources, a global data base accessible by all agents and containing all active processing data, and a control structure. Using the design capabilities of the blackboard, problem solving is incremental (a complete solution is constructed piece by piece and at different levels of abstraction) and opportunistic (the system makes control decisions in order to make the best progress toward meeting its goals, given the current situation).

Consequently, using the blackboard architecture for the KBS infrastructure in our implemented system, WEM can produce a guaranteed solution in real-time using goal- or data-driven algorithms. The MSDF/STA/RM prototype, which has been completed, makes use of the core KBS infrastructure, which is operational. As the prototype application evolves, the KBS infrastructure will also mature, with new KBS capabilities being utilised in subsequent builds of the application.

6.3 WEM Functionality

As discussed in Section 6.1, we are in the midst of an initial implementation of an integrated MSDF/STA/RM system that incorporates WEM based on the model described in Chapter 0. The blackboard KBS architecture described in Section 6.2 forms the infrastructure for this agent-based WEM component. This WEM component has two fundamental high-level tasks: the creation of plans and the implementation of plans. Inputs to WEM include threat data (i.e., results of Level 1 through Level 3 data fusion processing), data from the weapon subsystems (e.g., status), kill assessment from prior weapon engagements, and time. Also available are various a priori data sources, like encyclopaedic databases, doctrine databases, knowledge bases, etc. The output will be actions which describe what weapon resource is to be used, the threat to which it has been assigned, when it will be used, and any special tasking orders (e.g., fire control solution).

The KBS infrastructure has been designed with features which make it possible to provide the meta-reasoning capability depicted in Fig. 4. A "global control agent" is part of the KBS infrastructure upon which the WEM component is built. A "local control agent" is intrinsic to WEM, and negotiates with the global controller for the disposition of system resources by analysing the feasibility of cost/quality recommendations from the global controller, agreeing or disagreeing with the recommendations, and selecting a recommendation to enact. The global controller also negotiates concurrently with the MSDF and STA subsystems in the integrated system. The complexity of the negotiation process and analysis by the local controller will become more sophisticated with each successive build in our implementation.

Agents corresponding to weapon controllers produce atomic weapon actions at the lowest level of hierarchical task planning. These are order specific and unique to particular weapon subsystems, and are essentially independent of higher level planning and scheduling processes (i.e., Layers 1 and 2 in Fig. 5).

The generic characterizer and projector functionality is provided by the STA subsystem in the initial implementation of this integrated MSDF/STA/RM system.

The generic effector is represented by several functions. A monitor function looks for and assesses the impact of changes between projected and observed tactical states of the world. For example, it considers changes in sensor data (e.g., position and

velocity of a target), threat assessment (e.g., threat ranking), weapon system status, and whether or not a prior engagement was successful. Reactive planning in the initial implementation primarily incorporates CPF-like rules and doctrine for engageability calculations, target-weapon pairing, and weapon assignment. Reactive plan repair is differentiated from reactive planning primarily only with the use of deliberative planning over longer time horizons. The need for repair is triggered by the monitor function, and will consist of conditional rules inspired by the reactive planner, but may also utilise a simple greedy algorithm. A plan selector function chooses between, or guides the combination of, reactive and deliberative plans. Finally, a plan instantiation function selects the appropriate action to implement at a specific point in time.

Provision has been made in our initial implementation of WEM for a deliberative planning function. However, the recently completed prototype does not utilise a deliberative planner. For the moment, therefore, WEM is essentially restricted to Layer 2 in the layered architecture illustrated in Fig. 5. Consequently, only reactive planning is currently performed, with its associated limited time horizon. However, a deliberative planner will be provided in the next build of the prototype as part of the progressive evolution of the initial WEM implementation. A brief overview of the intended approach for the deliberative planner is given in the next section.

6.4 Development of a Deliberative Planner

As indicated in Section 6.1, we intend to incorporate deliberative planning in our initial implementation of WEM within an integrated MSDF/STA/RM system. This is the primary enhancement intended for WEM in the subsequent build of the prototype, and development of the planning algorithm has been proceeding as part of a concurrent, collaborative R&D effort with the Centre for Research on Transportation at the Université de Montréal. A brief overview of this work and how it can be implemented in our system follows.

The deliberative planner schedules the use of hardkill weapons and search and illuminating radars that must lock onto a target and, for SAMs, provide full course guidance from time of fire to intercept. Cues are generated over a pre-determined time horizon for allocating/releasing tracking and illuminating radars, and for firing a weapon. The planner's utility function currently optimises only for survivability, but later will consider other factors like resource conservation. Weapon use will follow CPF-like

engagement doctrine (e.g., shoot-look-shoot strategies for SAM firing). The planner generates cues which attempt to maximise the number of weapon engagements, subject to doctrine. The cues will also contain different action contingencies that depend upon the results of prior actions (e.g., whether or not a weapon has killed its intended target).

Starting from a perception of the tactical situation at the current time, there may be infinitely many potential evolutions of the battle world thereafter, each consistent with the current perception and each determining a feasible defence plan. Obtaining a solvable optimisation solution requires evaluation of a finite plan space, which entails producing a potentially sub-optimal plan. A finite set of cues are generated for CPF-like resources using a recursive algorithm developed in prior research (Refs. 17, 8). This algorithm is based on an enumerative search, which can be viewed as a tree traversal through various plan contingencies, sweeping backward in time over the set of feasible defence actions for the current plan horizon. The choice to search backward in time from a point close to ownship helps maximise the number of re-engagements of a threat, and allows intercepts to occur in regions of highest possible kill probability. The contingency tree of cues generated in this first step is then pruned subject to some general incompatibility conditions between cues, which reflect both technical constraints (e.g., some resource assignment conflicts) and doctrine (e.g., whether to allocate multiple fire channels to the same target).

We are currently investigating the use of a tabu search algorithm (Refs. 18-19) as the means to optimise the set of cues upon which to act. A simple heuristic is used to generate an initial solution, while tabu search is used to evolve and optimise the quality of the solution. A solution should be available at anytime, and the quality of the solution should essentially increase monotonically as the time and system resources available for deliberation increase. This algorithm also lends itself to parallelisation techniques. The results of this work are expected shortly, where we will be able to assess the impact of the quality of the initial solution, and the quality and efficiency of the optimisation. We are also exploring alternatives to the optimisation algorithm and the general techniques and configuration of the deliberative planner.

6.5 Closed-Loop Simulation Environment

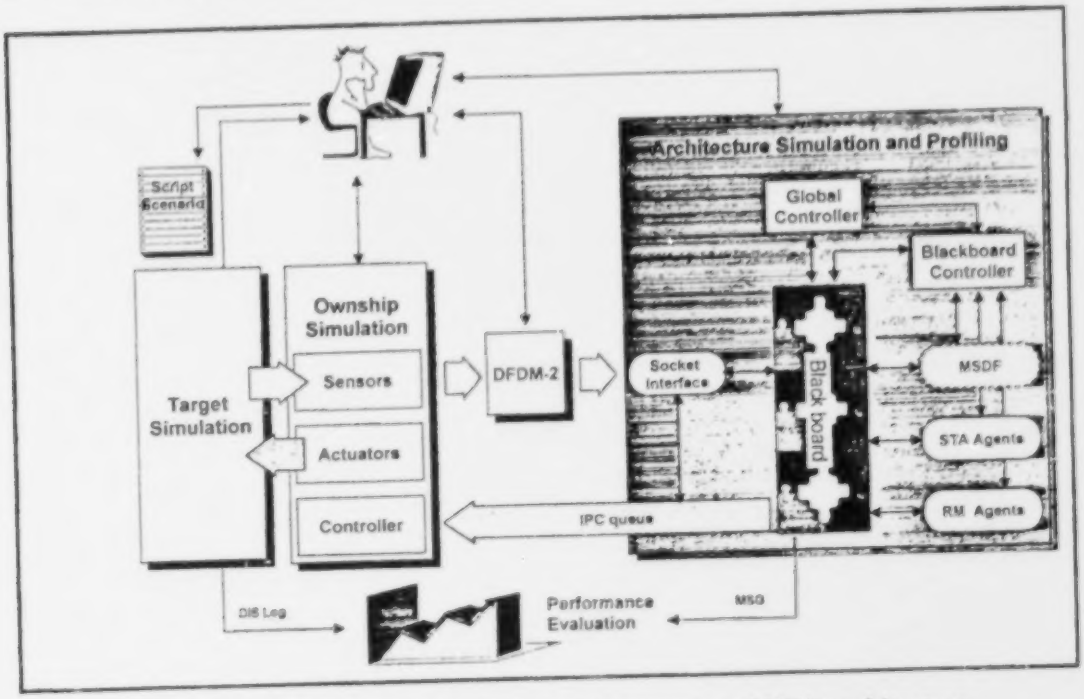
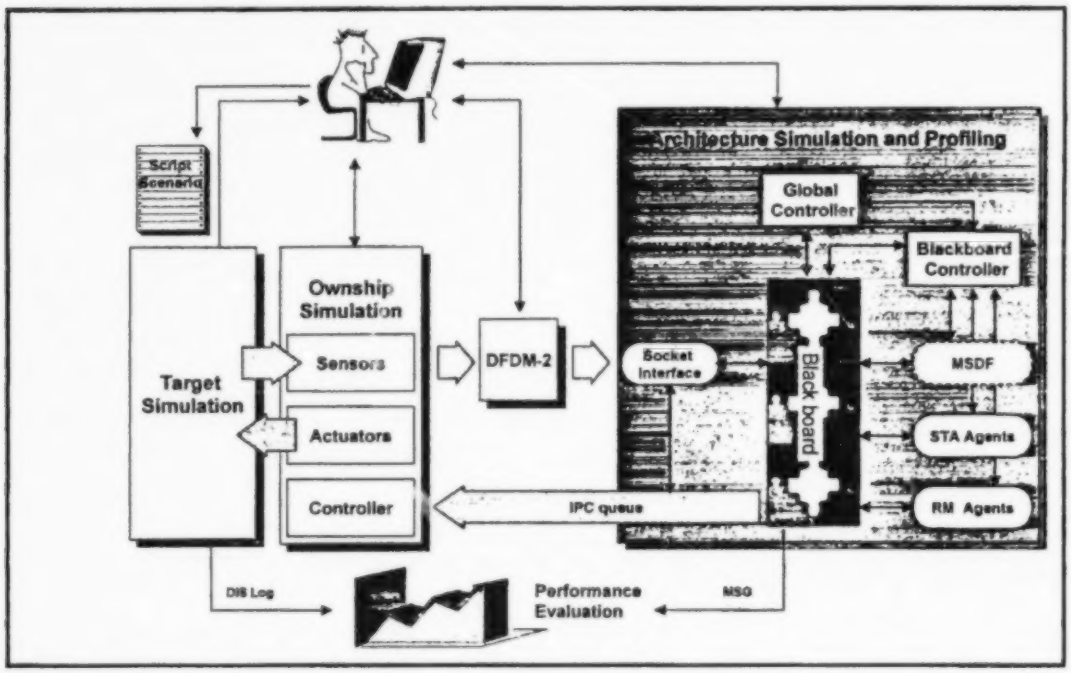


FIGURE 7 – Closed-loop simulation environment and KBS architecture

In order to test the performance of algorithms in the MSDF/STA/RM system, a versatile closed-loop simulation environment has been built and its functionality and capability continue to evolve. Currently, it comprises capabilities for target and ownship simulations and for scripting scenarios to which the ship must react, a performance appraisal capability, and the blackboard system described in Section 6.2. These various capabilities are illustrated in Fig. 7. DFDM-2 is the current MSDF implementation. The intention is to incorporate its functionality as an agent that interacts directly with the blackboard at a later stage. This particular agent is shown dashed in Fig. 7.

6.5 Closed-Loop Simulation Environment



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7.0 CONCLUSIONS

This document situated resource management issues for a ship within the context of the tactical shipboard Command and Control process. This led to defining the role of weapon engagement management in Above Water Warfare. This role constitutes a capability of a real-time decision support system that is currently being designed, developed and implemented to support operators in their tactical decision making and action execution activities.

A high-level generic model of weapon engagement management was also presented. In this model, the manager plans and directs in real time actions involving use of hardkill and softkill weapons to counter air and surface threats. An agent architecture that dynamically interleaves planning and execution as it adapts to unanticipated changes in the tactical situation has been proposed. The architecture integrates both reactive and deliberative planning. Deliberation is based on projecting the currently perceived situation and may incorporate plan contingencies to handle action outcome and situation uncertainty. Reactive planning is driven by precompiled stimulus-response knowledge (e.g., tactical doctrine).

The preliminary success in implementing the decision support system has, to the limited extent possible so far, demonstrated the viability of this model of weapon engagement management. A unique Knowledge-Based System based on a blackboard architecture provides the infrastructure for the implemented system. Both the completed MSDF/STA/RM system prototype and the Knowledge-Based System are in the process of evolving. After a series of successive builds our initial implementation of WEM, although somewhat simplified relative to the complete scope of weapon engagement management concerns (e.g., anti-air warfare only, and no softkill weapons), will utilise all elements of the generic architecture for weapon engagement management presented in this document.

The results of this research are of particular importance for a mid-life upgrade of the Canadian Patrol Frigate expected early in the next century. Moreover, they are also relevant to any consideration of weapon engagement management in Above Water Warfare for a naval platform.

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13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

DREV, in collaboration with Lockheed Martin Canada, is investigating the development of a computer-based, real-time decision support system that can provide advanced support capabilities for combat system operators in countering the current and anticipated threat to the Canadian Patrol Frigate. Among its principal roles, this system will: continously take in data from the ship's sensors and other information sources; support the fomulation, maintenance and display of an accurate tactical picture derived by fusing all available data, leading to enhanced situation awareness; and assist with the determination and selection of a response to anticipated or actual threats. This document is concerned with the development of a weapon engagement manager for Above Water Warfare that forms part of the system. The manager adaptively plans and directs in real time actions to counter air and surface threats. A generic agent architecture is introduced and current work toward its implementaiton and performance evaluation in a closed-loop simulation environment incorporating a custom-designed knowledge-based shell is described.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each sould be indicated as with the title.)

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Weapon Engegement Management
Command and Control System
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